



Matching sherds to vessels through ceramic petrography: an Early Neolithic Iberian case study



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ABSTRACT

Ceramic re-fitting has traditionally focused on linking sherds to vessels using their formal features or decoration. This paper presents an innovative procedure designed to test such associations using ceramic thin section analysis. An assemblage of the earliest hand-made ceramics from central Iberia dated to the second half of the 6th millennium BC was used as a test case. First, the whole ceramic assemblage was subjected to macroscopic morphological sorting, taphonomic evaluation and a re-fitting operation. These tasks led to the recognition of both secure physical joins and probable matches. 16 sherds, representing 8 pairs, were selected from among those probable matches. These samples were investigated by thin section petrography and the photomicrographs processed using digital image analyses to produce qualitative mineralogical and quantitative textural data for assessing the likelihood of each pair belonging to the same vessel. The results show the potential of this strategy for matching sherds to vessels, as well as its reliability and wide applicability.

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1. Introduction

Pottery re-fitting constitutes a well tested and efficient post-excavation analytical method, becoming widespread in the last decade (e.g. Sullivan, 1989; Bollong, 1994; Garrow, 2006; Edwards, 2012). This is the most suitable strategy to address important archaeological questions, such as stratigraphic and formation processes, the cultural choices related to the management of waste, or the in-depth characterization –temporality, scale, frequency, etc.– of past depositional practices. This approach was originally borrowed from the *chaîne opératoire* method, aimed at reconstructing Palaeolithic technological débitage (Chapman and Gaydarska, 2007: 85–87). Lithics and ceramics are, however, very different archaeological materials whose methods of study are often not interchangeable. Thus, an uncritical reliance on the original lithic studies has been detrimental to the development of ceramic re-fitting. Particularly, sherd-links have been addressed through an almost exclusive emphasis on diagnostic sherds, such as rims, carinations, bases, etc., since ‘body sherds are often

impossible to match’ (Orton and Hughes, 2013: 266). Moreover, the focus for linkages is most often on sherds that can be directly adjoined or matched. This perspective has narrowed the understanding of results achievable from sherd re-fitting, leading to an underappreciation of the broad informative potential of this practice (Blanco-González and Chapman, 2014). Indeed, secure ceramic matches constitute a rare, random and unrepresentative subset (Sullivan, 1989: 104) out of the array of associations actually recognizable between potsherds, necessitating the development of methods that can securely identify these associations.

The above shortcomings have rarely been addressed by scholars. Bollong’s scoring method (1994: 17–19, Table 1) is one of the few and most notable contributions on this subject to date. This author defined six types of sherd-to-vessel associations ranging from actual physical refits to more uncertain linkages and isolated examples with no association in the assemblage, known as ‘orphan’ sherds. However, his scheme relies heavily upon visual impressions expressed in qualitative indexes, inhibiting an independent evaluation of the results. Moreover, Bollong does not pay adequate attention to body sherds with no physical matches, which represent the bulk of potsherds in any ceramic assemblage. Ceramic thin section analysis could be a strategy well suited to

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Table 1

Ceramic samples from La Lámpara, stating their archaeological context, description and the questions addressed through their study.

Sample	Accession no.	Context	Reference	Description	Addressed questions
A	97/8/C/175	Pit 1	Rojo et al. 2008: 158, Fig. 130, no. 8	Incised rim sherd with light orange surfaces	Sherds from the same hemispheric bowl in different pits (25 m apart)?
B	99/197/E-404/1	Pit 3	Rojo et al. 2008: 158, Fig. 130, no. 3	Incised rim sherd with homogeneous dark color	Differential post-breakage alteration (by fire in Sample A)?
C	2001/125/3.2.1.2	Pit 9	Rojo et al. 2008: 150, Fig. 122, no. 10	Grooved body sherd from a hemispheric bowl with homogeneous light brown-orange color	Sherds from the same hemispheric bowl within the same Pit 9? Differential post-breakage alterations by fire?
D	2001/125/3.2.1.1	Pit 9	Rojo et al. 2008: 150, Fig. 122, no. 4	Grooved rim from a hemispheric bowl with uneven gray color	
E	99/197/E-406/4	Pit 3	Rojo et al. 2008: 150, Fig. 122, no. 11	Grooved rim from a hemispheric bowl with even gray color	Sherds from the same hemispheric bowl in different pits (30 m apart)?
F	2001/125/2.13.12	Pit 13	Rojo et al. 2008: 150, Fig. 122, no. 7	Grooved rim from a hemispheric bowl with uneven gray color and clear post-breakage sooting	Differential post-breakage alterations (by fire in Sample F)?
G	2001/125/7.5.1.2	Pit 17	Unpublished	Coarse, handled, body sherd with gray color, rounded edges, porous surfaces and intense fire disturbance	Sherds from the same coarse handled vessel within Pit 17? Differential post-breakage alterations (abrasion and fire in Sample G)?
H	2001/125/7.6.1.3	Pit 17	Rojo et al. 2008: 139, Fig. 114, no. 2	Coarse, handled, body sherd with homogeneous color, fresh edges and smooth polished surface	
I	99/98/D-302/14	Pit 2	Unpublished	Plain body sherd with light orange color	Sherds from the same vessel in different pits (45 m apart)? No post-breakage alterations
J	99/98/B-202/82	Pit 10	Unpublished	Plain body sherd with light orange color	
K	2001/125/2.3.1.2	Pit 13	Rojo et al. 2008: 158, Fig. 130, no. 4	Incised rim dark gray sherd, worn surfaces and breaks.	Sherds from the same bowl in different pits (10 m apart)? Differential post-breakage alterations (abrasion in Sample K)?
L	2001/125/1.1.1.1	Pit 18	Unpublished	Incised body light gray sherd	
M	2001/125/2.11.1.4	Pit 13	Rojo et al. 2008: 163, Fig. 134, no. 2	Incised rim sherd with pale orange color	Sherds from the same hemispheric bowl within the same Pit 13?
N	2001/125/2.10.1.3	Pit 13	Rojo et al. 2008: 163, Fig. 134, no. 3	Incised body sherd with dark gray color	Differential post-breakage alterations by fire?
O	2001/125/2/11/1/1	Pit 13	Rojo et al. 2008: 140, Fig. 115, no. 1	Irregularly fired rim sherd from a large vessel with impressed lip and impressed plastic applications, fresh edges and fractures	Sherds from the same large decorated vessel within the same Pit 13? Differential post-breakage alterations (abrasion in Sample P)?
P	2001/125/2/12/1/2	Pit 13	Rojo et al. 2008: 140, Fig. 115, no. 1	Irregularly fired rim sherd from a large vessel with impressed lip and impressed plastic applications, eroded edges and fractures	

tackling these concerns; it has been widely used to characterize pottery production technology and even post-depositional alterations (e.g. Orton and Hughes, 2013: 172–173; Quinn, 2013: 204–210). Yet, petrography has never been deployed to characterize the pre-depositional processes that take place between the time vessels are fractured and their definitive discard. This paper contributes towards this endeavor. First a visual assessment and a re-fitting operation were carried out with a collection of hand-made ceramics. Then, 16 non-conjoining paired sherds were selected, sectioned and petrographically examined. Subsequently their photomicrographs were processed through digital image analyses. A scanning electron microscope was used to compare the nature of some mineral inclusions. This procedure has allowed for the testing of several hypothetical sherd-to-vessel associations with important consequences for understanding how these ceramics entered the archaeological record. This new method suggests that there is much to learn from these often disregarded stages of the life-cycle of archaeological ceramics, which have been referred to as their ‘life after the break’ (Chapman and Gaydarska, 2007: 81–112).

2. Materials and methods

An awareness of the above mentioned issues prompted the design of an alternative method. This method focuses on non-adjoining sherds irrespective of their shape or quality and pays special attention to the terminal steps of their use-lives, i.e. after they became detached fragments. A threefold procedure was developed that combined mainstream macroscopic aspects and a microstructural compositional approach, which incorporated: a) an initial systematic qualitative examination of the entire ceramic collection, including a re-fitting experiment and a complete taphonomic evaluation. This led to the identification of direct or physical joins and non-physical but highly probable matches; b) the selection among the highly probable but non-adjoining matches of sherd-pairs representing a suite of sherds types and taphonomic alterations, aimed at tackling a series of research questions, and c) the use of thin section petrographic examination and the digital image analysis of photomicrographs to verify the previous observations in qualitative mineralogical and quantitative textural terms.

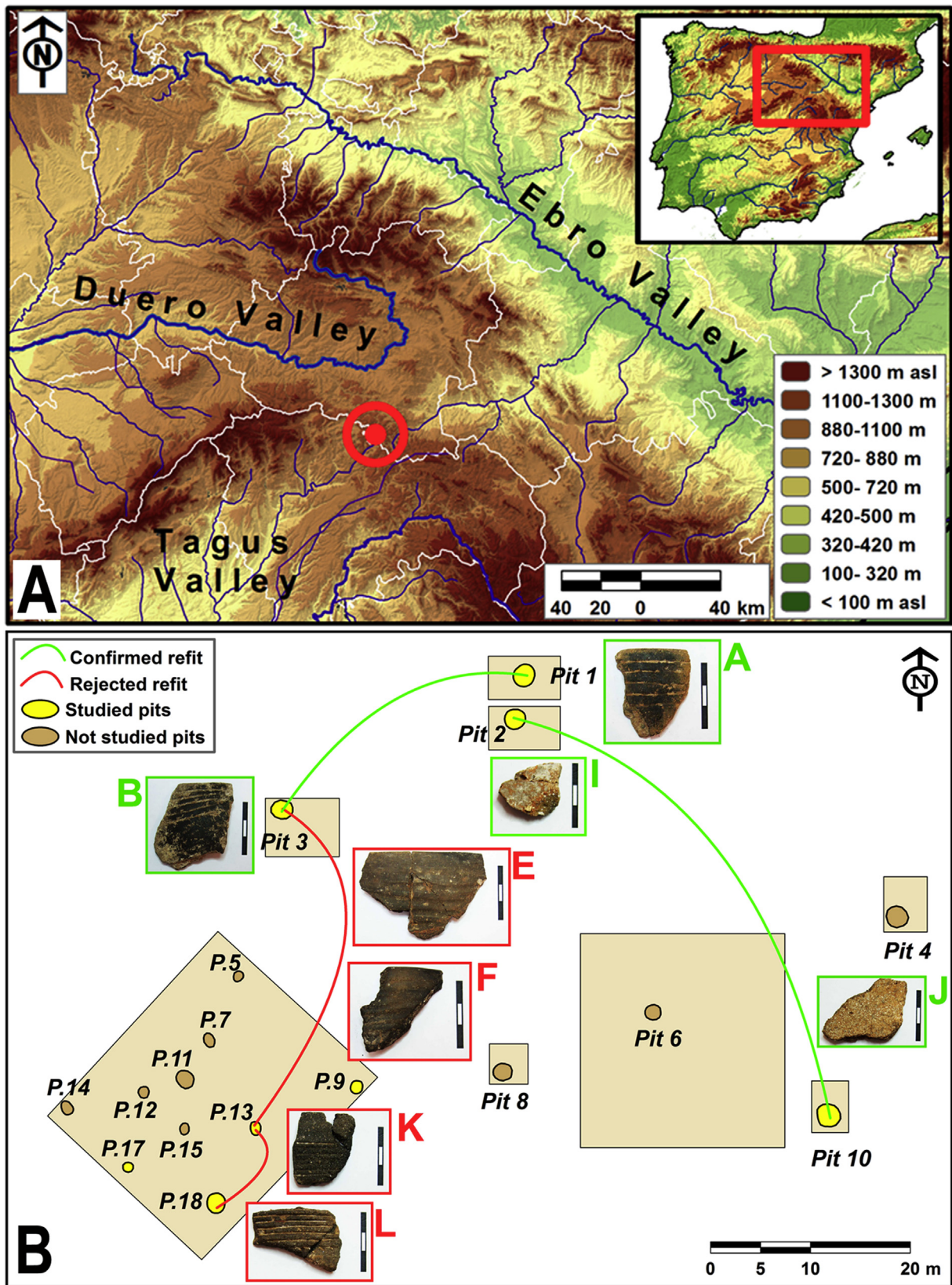


Fig. 1. A. Location of La Lámpara in inner Iberia (Spain). B. Excavated sectors, pits with ceramics studied using the proposed method, and inter-feature refitting sherds (after Rojo et al., 2008: 80).

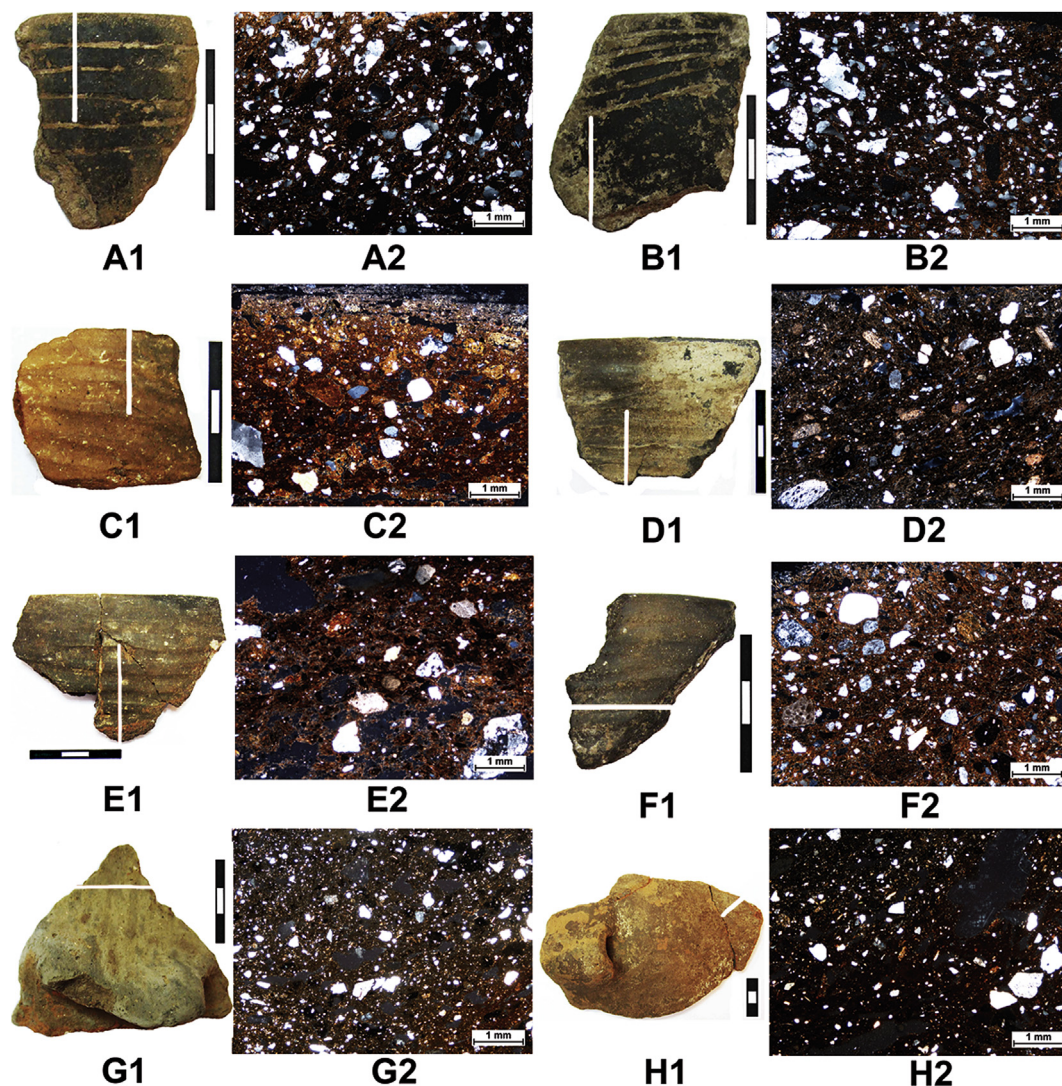


Fig. 2. Sherd samples A to H and respective photomicrographs in cross polarized light. White lines indicate from where sample slices have been obtained. Scales in cm.

Once the procedure was designed, samples were selected to test a series of hypothetical sherd-to-vessel associations. These samples were also chosen because their analysis would inform on important aspects of site formation processes and prehistoric cultural practices dealing with the management of refuse and the reuse of ceramics after their break. In particular, we were interested in characterizing the completeness of vessels among the surviving debris. Patterns of diminution and discard of ceramics were also investigated in order to understand their temporality, dispersion and degradation before deposition. The Early Neolithic ceramic assemblage from La Lámpara (Soria, Spain) represents a suitable case study since it meets a series of basic criteria: a) it is relatively small and manageable allowing for a systematic re-fitting and taphonomic assessment; b) it consists of abundant decorated sherds, including already tested re-fitting fragments, many of them showing a variety of post-breakage alterations, and c) all the ceramic collection was carefully documented and fully published, and ceramic items were retrieved from multiple undisturbed depositional contexts. La Lámpara is a pit site located at a strategic crossroad from the Mediterranean coast to the Iberian central Meseta (Fig. 1A). Excavations in the late 1990s

unearthed 18 pits dug in the geological subsoil (Fig. 1B), some of them probably used as ground storage silos that were subsequently backfilled with settlement debris (Rojo et al., 2008: 379–393). These cut features yielded one of the earliest ceramic collections from Iberia. This seasonal camp was reoccupied all through the second half of the 6th millennium BC according to a series of 24 radiocarbon assays – including short-lived samples – from seven pits. It was inhabited by small agro-pastoral groups whose subsistence was based on mixed farming –especially wheat and barley (Stika, 2005) –, the herding of goats and sheep and some hunting and gathering (Rojo et al., 2008). In short, this ceramic sample testifies to the earliest occupation of farmers introducing Neolithic socio-economic innovations into the inner tablelands of Iberia.

2.1. Re-fitting and taphonomic operations

Research conducted at the Museo Numantino (Soria, Spain) allowed for the study of the whole ceramic assemblage recovered at La Lámpara during the 1997, 1998 and 2001 excavations. The examination was aimed at thoroughly characterizing the patterns

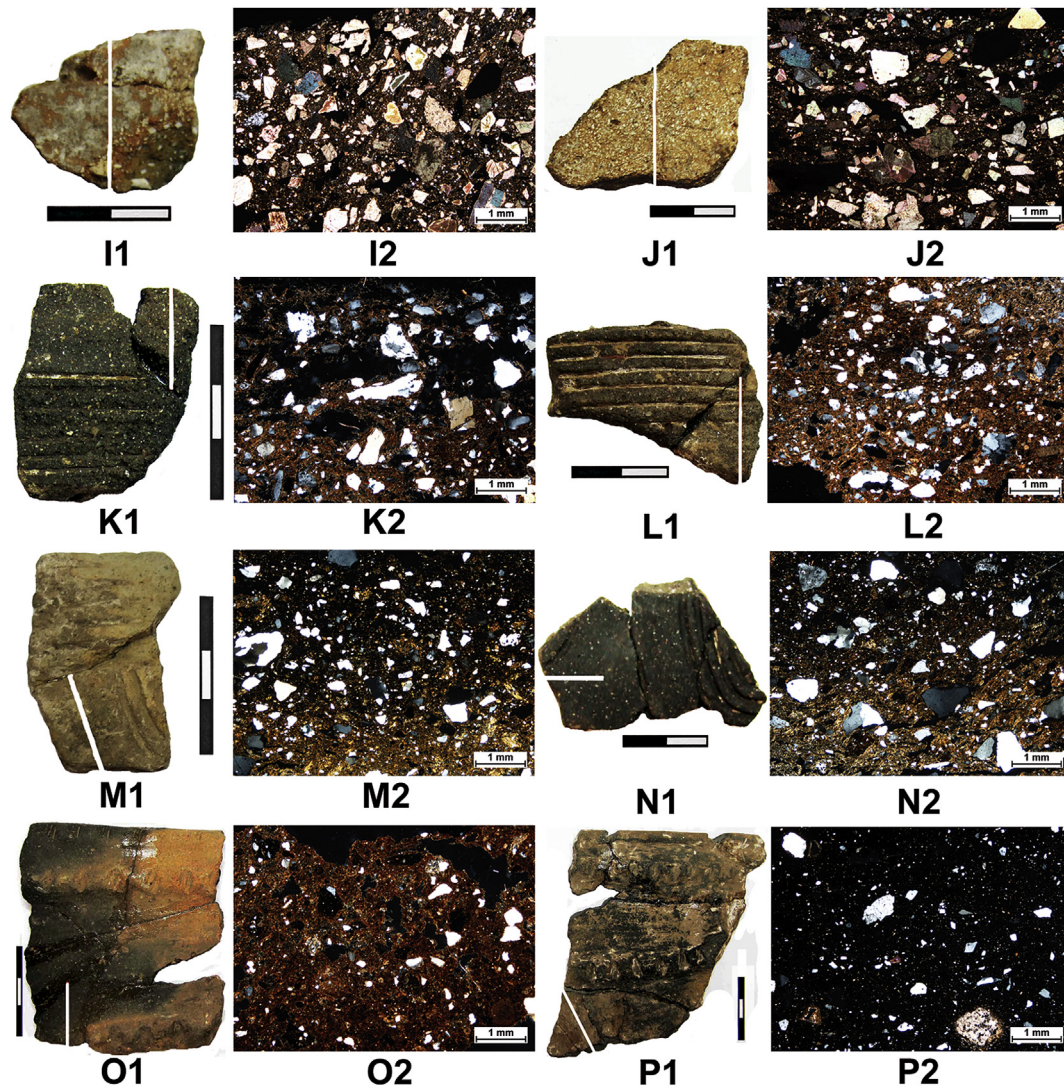


Fig. 3. Sherd samples I to P and respective thin section photomicrographs in cross polarized light. White lines indicate from where sample slices have been obtained. Scales in cm.

of fragmentation, as well as the alteration and eventual deposition of ceramics. Some of these dynamics had been regarded by the excavators as very likely deliberate, rather than random (Rojo et al., 2008: 375). The re-fitting experiment involved 1349 potsherds, derived from a minimum of 64 vessels (García et al., 2011: 86). The identification of sherd-links focused on the systematic optical comparison of attributes –e.g. thickness, decoration, surface treatment, core color and inclusions, etc. – between sets of sherds observed with a hand-lens, filling in a scoring template that has been presented elsewhere (Blanco-González and Chapman, 2014). This allowed the recording of a total of 72 such sherds-to-vessel associations, each one involving between 2 and 42 sherds: 148 cases constituted ‘physical’ or ‘directly’ adjoining sherds, including already glued pieces (e.g. Rojo et al., 2008: 381), whereas 206 represented sherds that could not be physically matched, but arguably belonged to the same vessels. Only old fractures were considered. Regarding the contexts of deposition, out of the 72 sherds-to-vessel associations the bulk of them (67 cases) are intra-feature refits, between sherds within the same pit, and 5 cases represent cross-feature refits, which

linked sherds from different pits (Fig. 1B). Regarding the taphonomic assessment, despite the effect of further post-abandonment fractures – probably due to their low firing temperature – the fragments are, on average, fairly large ($>12\text{ cm}^2$). The majority of the sherds are well preserved, exhibiting fresh edges and only residual abrasion. Importantly, an exhaustive examination led to the identification of pre-pit disturbances such as attritional marks left by open-air weathering or differences in color between sherds due to burning. Since such alterations also affect the breaks of the sherds, technological or use-wear causes can be rejected – they are to be confidently ascertained as post-breakage degradation. A few such cases were recognized between probable re-fitting sherds.

2.2. Sampling for petrographic examination

Out of the 206 non-conjoined pieces, a total of 16 sherds were subjected to thin sectioning for petrographic analysis (Table 1, Figs. 2 and 3). The samples consisted of decorated and plain rims and body sherds from both fine and coarse wares from eight

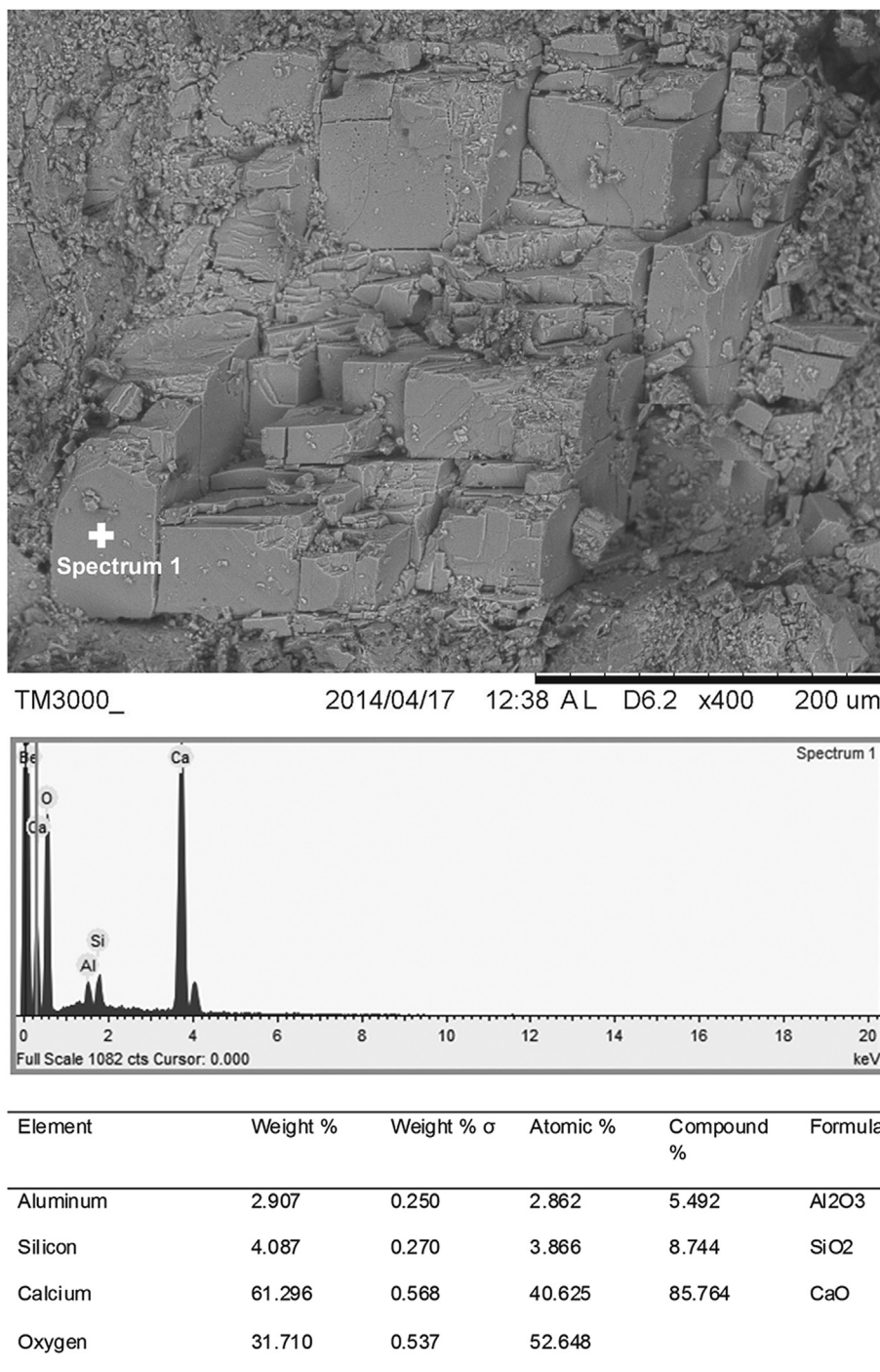


Fig. 4. Back-scattered scanning electron image of sample J showing a monocrystalline grain of calcite. The EDS spectrum and bulk chemical composition are included.

different features (Pits 1, 2, 3, 9, 10, 13, 17, 18) (Table 1 and Fig. 1B). Samples were named from A to P, forming pairs of non-physically matching sherds suspected of belonging to the same vessels. These sherds were strategically chosen to test the reliability of the preliminary macroscopic observations through a more thorough assessment. They were also selected to verify whether some of the above mentioned post-breakage alterations might have impeded comparisons between sherds, thus restricting the applicability of the proposed procedure. Three specific archaeological questions were addressed (Table 1) through the selection and sampling of specific pairs of sherds:

- Whether sherds from the same vessels can be found in different pits (pairs A & B; E & F; I & J; K & L). A positive result – i.e. they are from a common vessel – would contribute to assessing the mobility of ceramics on the site and indicate the contemporary backfilling of these pits (Bollong, 1994; Garrow, 2006; Orton and Hughes, 2013: 265). A negative result would require further refinement in the methods of macroscopic comparison between sherds.
- Whether sherds from the same vessels can be found in the same pit (pairs C & D; G & H; M & N; O & P). If they actually belonged to the same vessels they might have been handled and

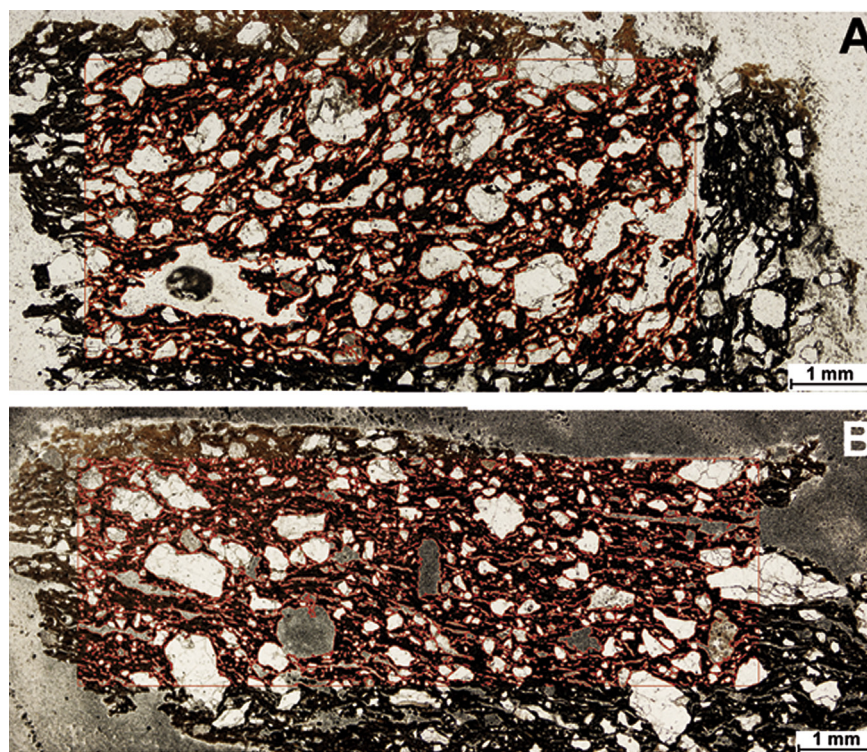


Fig. 5. Photomicrographs of the digital image analysis from samples A & B showing the polygons created by the software around the grains and voids. The digital image software creates a binary image, differentiating the grains and voids from the matrix, then creates polygons around the pixel values representing the grains. The percent area of grains and voids to matrix and the total number of grains are then calculated.

discarded together after breakage. If, on the contrary, they derive from different vessels, it might indicate the joint disposal of similarly looking decorated sherds.

- c) Whether sherds with contrasting appearance due to pre-depositional and clearly post-breakage alterations –abrasion and burning– can be shown to originate from a common vessel (pairs A & B; C & D; E & F; G & H; K & L; M & N; O & P) (Table 1). A positive outcome will indicate disparate life-paths – e.g. middening or reuse of fragments (cf. Chapman and Gaydarska, 2007: 75–77; Garrow, 2006; Edwards, 2012) prior to their definitive discard.

Pairs of conjoining sherds might have provided with a control test to check the results of the petrographic and digital image analyses. However, the sampling strategy of one of the earliest ceramic assemblages in central Iberia – with many of the selected sherds being decorated – was strongly limited by curatorial requirements. Thus, instead of allocating time and resources to analyze adjoining sherds – whose results would be predictably very close –, characterizing a collection of the far more problematic non-conjoining sherds as wide as possible and representative of diverse research topics was considered priority.

2.3. Petrographic analysis

Petrographic analysis focused on the composition of fabrics characterizing the types, amounts, size ranges, roundness and sorting of non-plastic inclusions and types of accessory minerals. The microstructure of the clay matrices were also examined, such as the shape, orientation and size of voids, distribution of inclusions within the fabric and signs of raw material preparation (e.g. incomplete kneading of clay or mixing of different clays). A

Nikon Eclipse LV100 polarizing microscope equipped with a Nikon DS Fi1 digital camera was used for the analysis. The raw materials, tempers and raw material preparation were examined for each ceramic pair. During petrographic analysis, the quantity of inclusions, their size categories, the degree of sorting and roundness of the components were determined in accordance with the guidelines of the Prehistoric Ceramic Research Group (2010: 21–27). A Hitachi TM3000 scanning electron microscope (henceforth SEM) fitted with a SwiftED3000 energy dispersive X-ray spectrometer (henceforth EDS) was used to analyze and compare the carbonate fraction in samples I & J. This was necessary because calcite and dolomite are difficult to differentiate under the optical microscope, especially when the calcite has been crushed and added as temper forming euhedral rhombs, which are often more typical of dolomite (Gribble and Hall, 2003: 154). If the carbonate fraction was found to be the same in both samples it could serve to indicate sherds I and J originated from the same vessel. The accelerating voltage was set to 15 kV and the probe current was set to 700 pA. The compositional analysis (Fig. 4) was generated by the SwiftED software using standardless matrix corrections and is semi-quantitative.

The following methodological considerations were taken into account: first, we considered that different parts of vessels may have been made from different raw materials since this practice may appear in hand-made vessels (e.g. Tobert, 1988: 65). It seems that there is no evidence for this practice for Iberian Neolithic ceramics. Therefore, sherds that were matched without doubt in terms of morphology and macroscopic fabric analysis but show slight differences during microscopic analysis could still have come from different parts of the same vessel. It must be noted that the composition and other petrographic characteristics within the fabric of the same vessel could be slightly

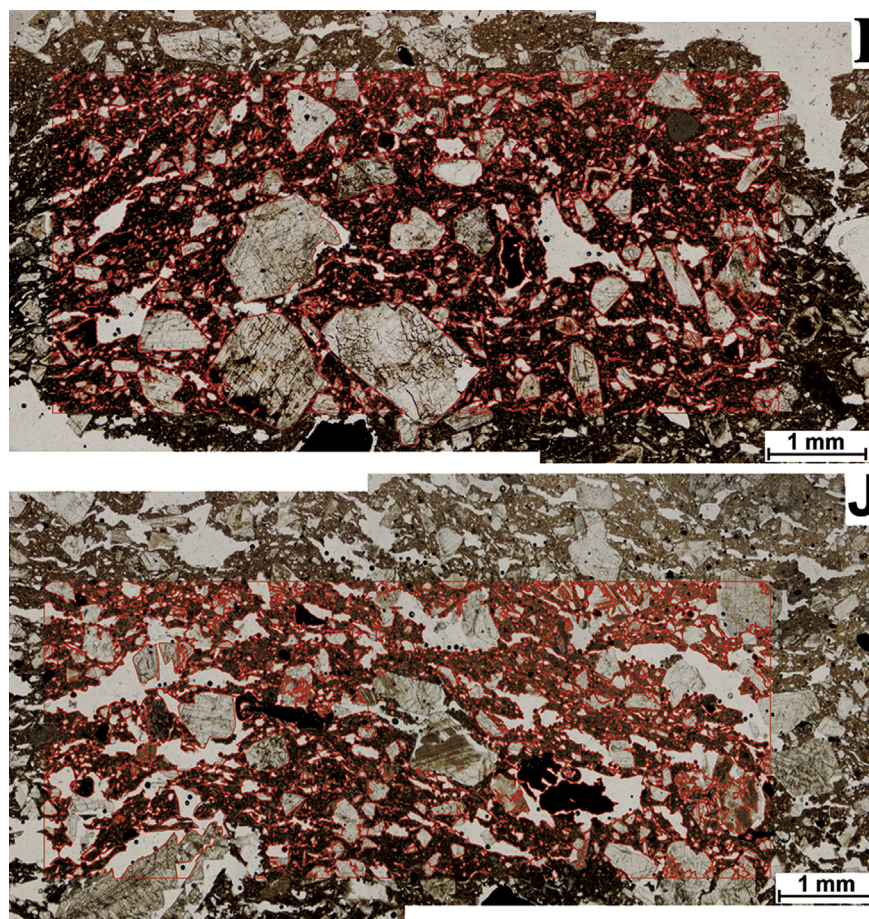


Fig. 6. Photomicrographs of the digital image analysis from samples I & J showing the polygons created by the software around the grains and voids.

different and may suggest that the samples belong to different vessels, when in fact they belong to the same one. It should be acknowledged that minor compositional differences in fabrics may be the result of natural heterogeneity of the original raw material or incomplete raw material preparation. The latter was often identified during the analysis: inclusions gathered in groups, drying cracks appear in the clay matrix. Therefore, while pairing the sherds all petrographically observable features were considered including microstructural characteristics that could be used to assess possible similarities or differences. We acknowledge that this approach is subjective and depends on the experience of the analyst but in many cases this seems to be the most effective means of assessing the complex characteristics of ceramics. Moreover, many textural and microtextural criteria, which can be particularly important in re-fitting do not always allow appropriate numerical definitions (see Quinn, 2013, 71–73).

2.4. Digital image analysis

In order to provide supporting evidence for the hypothesis that paired sherds in the assemblage originated from common vessels, digital image analysis was used to contribute further quantitative data. As mentioned above, the clay used to make vessels is often heterogeneous. Still, if two sherds originate from the same vessel, elements of the microtopography, such as grain distribution (sorting) and the ratio of non-plastic inclusions and

voids to clay matrix should be roughly equivalent in random samples from the same vessel, as this would reflect clay prepared using materials from a similar geological source or sources and similar paste preparation by the potter (Quinn, 2013: 102–106).

A number of software programs exist for the quantitative textural description of petrographic samples. The program Jmicrovision¹ was used here to quantify the number of non-plastic grains and voids and their total area as a percentage within the sample. Photomicrographs taken during the petrographic analysis were used for image processing. The data were taken from image analyses conducted on photomicrographs taken in plane polarized light. Images taken under crossed polarized light were also processed as a check. The results were found to be similar for every sample. The individual photomicrographs were tiled together to create highly magnified, but extensive images for processing (Figs. 5 and 6). Digital image analysis (Reedy and Kamboj, 2003; Reedy, 2006) was carried out on all the ceramic samples described above and the quantitative values generated were compared for each sherd pair.

To complete the image analysis the photomicrographs were first imported into the software and converted to simple binary

¹ Jmicrovision is a freeware digital image analysis application (www.jmicrovision.com) designed by Nicolas Roduit as part of a doctoral thesis (Roduit, 2007). This program was chosen because it has a large number of options and an intuitive user interface compared to other freeware platforms, like ImageJ.

(black and white) images using the image processing tools imbedded in Jmicrovision. Transparent minerals and voids are made black and the clay matrix white. Non-linear filtering was used on some of the color images to better separate grains from the matrix. The software then processes the image, drawing polygons around each individual grain (Figs. 5 and 6), and calculates the number of grains and voids and the total area occupied by them. These quantitative values were then compared directly between pairs of sherds to test the qualitative microscopic and macroscopic assessments of the samples described above. Where the results were similar the sherd pairs were considered likely to have originated from a common vessel. A quantitative value that signifies two sherds originate for the same vessel is difficult to provide, as little experimental data has been produced in this regard. For the purposes of this study, we considered that if the difference in the value of total area percentage of non-plastics and voids between two samples were <3% it represented a strong match. If the analysis produced values of >5% between two samples the results were considered to represent a very poor match. Intermediate results between these two numbers were inconclusive. The outcomes of this analysis are presented in the [Appendix](#).

For normalization and inter-sample comparative purposes, the analyses were conducted in a rectangular area measuring 25 mm² on each sample (Figs. 5 and 6) because it was the largest possible area of analysis on the smallest samples in the set. The areas were always rectangular, but due to the irregularity of the samples and the random presence of uncharacteristic features, such as unusually large voids, areas of slightly differing shapes were analyzed for each sample. Tests were, however, conducted in different parts of some of the larger samples, and an analysis area of 25 mm² provided reproducible results, intra-sample. Some grains, like shales or rock fragments, cannot easily be separated from the matrix using this method and the shapes were drawn by hand. It should also be noted that this method does not provide a total quantification, as the silt fraction cannot be reliably measured due to the magnification limits of a light microscope.

3. Results and discussion

The petrographic results are discussed for each of the ceramic pairs, highlighting their main features, which serve to link or separate them from each other.

- 1) Samples A & B (Fig. 2, A1–B2). The types of inclusions are similar and both samples are tempered with quartz sand. The accessory minerals, sorting, characteristics of voids, matrix color and homogeneity are similar. Therefore, petrographically they seem to be part of the same vessel. Image analysis also indicates a strong match between them (Fig. 5 and [Appendix](#)).
- 2) Samples C & D (Fig. 2, C1–D2): Both sherds are tempered with quartz sand. They also contain rounded argillaceous rock fragments (Whitbread, 1986) (henceforth ARFs). The similarities in sorting, characteristics of voids and ARFs suggest that they might have belonged to the same vessel. Image analysis, however, indicates a poor match between these samples ([Appendix](#)).
- 3) Samples E & F (Fig. 2, E1–F2): Both items are tempered with quartz sand although the size and amount of the inclusions differ considerably. Moreover, the size and direction of cracks and the ARFs are different. Therefore, these samples are probably parts of different vessels. Image analysis also indicates a poor match ([Appendix](#)).

- 4) Samples G & H (Fig. 2, G1–H2): Both sherds show a very fine-grained fabric and are quartz sand-tempered. They also contain grog/ARFs. In spite of the uneven distribution of non-plastic inclusions (a result of quartz sand tempering), the characteristic elongated voids and the orientation in the matrix suggest that these samples may have been part of the same vessel. Image analysis also indicates a strong match between them ([Appendix](#)).
- 5) Samples I & J (Fig. 3, I1–J2): Both samples feature calcareous inclusions, with identical, abundant amounts and size of calcite, as identified by analysis with the SEM-EDS (Fig. 4), probably added as a temper. These samples show the closest resemblance among those examined; they most probably belong to the same vessel. Image analysis also points to a strong match between them (Fig. 6). The SEM-EDS analysis supports our assessment of a common origin.
- 6) Samples K & L (Fig. 3, K1–L2): Both sherds are tempered with different amounts and sizes of quartz sand. In Sample K, however, the fine-grained inclusions are almost missing, mainly very fine and medium grains can be observed. In Sample L the majority of inclusions are very fine, followed by medium grains. These differences indicate that these items are probably from different vessels. The image analysis results were inconclusive due to the presence of large voids in Sample K ([Appendix](#)).
- 7) Samples M & N (Fig. 3, M1–N2): Both pieces are quartz sand-tempered, and despite differences in the amount and size of inclusions, similarities in the characteristic elongated and oriented voids and the sparse amounts of medium-coarse yellowish ARFs indicate that they may belong to the same vessel. Image analysis also indicates a strong match ([Appendix](#)).
- 8) Samples O & P (Fig. 3, O1–P2): Clays of these sherds are different despite both being tempered with sand, mainly composed of quartz and including a calcareous fraction. Sample O has a clay-rich fabric while Sample P has a very fine-grained matrix containing mainly quartz. Sample P also shows characteristic elongated voids absent in Sample O. Image analyses also indicates a poor match between them ([Appendix](#)).

The raw materials used and the techniques of production seem quite similar among the studied collection. The majority of these ceramics were tempered with quartz sand and often with grog. To distinguish between grog and argillaceous inclusions (ARFs) Whitbread (1986), Cuomo di Caprio and Vaughan (1993), Kreiter and Tóth (2010) and Kreiter et al. (in press) worked out a series of criteria. According to them, both grog and ARFs appear in the samples. Grog tempering has been previously reported in Early Neolithic pottery in northern and inner Iberia (Ortega et al., 2010: 992; Díaz-del-Río et al., 2011: 107). The composition of grog inclusions in the La Lámpara samples is similar to the clay in which they are incorporated. This phenomenon has been noted both in ethnography and archaeology (Sillar, 1997: 12; Kreiter, 2007: 130). In the case of ARFs, it seems that potters did not adequately prepare the raw material, and therefore some hard clay pieces did not mix and homogenize with the clay. Thus, variability within the fabrics seems to be the result of differences in quartz sand and grog tempering and incomplete raw material preparation, which resulted in inclusions forming groups within the fabric (Kreiter et al., in press) and cracks and voids from inadequate kneading and drying before firing.

There is broad agreement between the overall petrographic results and the digital image analysis. The eight hypothetical sherd-to-vessel associations have been soundly tested and it is

time to resume the archaeological questions raised in Section 2.2 (Table 1). First, the hypothesis that sherds belonging to the same vessel might have eventually entered in distant features has been demonstrated in two instances: a fine incised bowl whose sherds A & B were found within pits 25 m away (Figs. 1B and 2) and two pieces (I & J) from a coarse vessel distributed in pits 45 m apart (Figs. 1B and 3). These cases confirm the mobility of the broken ceramics before deposition. Another four sherds (E, F, K, L, Figs. 1B, 2 and 3) have offered negative outcomes – i.e. they belonged to different vessels. There is also evidence for the incorporation of fragments of the same vessels in the same features, such as sherd pairs G & H (Fig. 2) and M & N (Fig. 3). Samples C & D may also represent fragments of the same vessel incorporated into Pit 9, as they are petrographically very similar (Fig. 2), but their image analysis is inconclusive. By contrast, the large slabs O & P (Fig. 3, O1 & P1), found in Pit 13, exhibit very similar applied and impressed rope decoration and were published as parts of the same vessel by the excavators (Rojo et al., 2008: 140, Fig. 115), but our analyses show that they actually derived from two different large coarse vessels. The occurrence of sherds with contrasting appearance – degree of preservation, external color – deriving from a common original vessel has also been confirmed. Sample G was heavily abraded and intensely burnt, whereas Sample H was ‘freshly’ broken and well preserved (Fig. 2, G1 & H1). Despite these striking contrasts, the analysis showed that they came from a large storage vessel. Such intense attritional degradation – due to open-air mechanical abrasion – could not occur naturally within the dug-out features (Edwards, 2012: 89) and there was no evidence of burning inside Pit 17. Therefore, it seems reasonable that both sherds underwent diverse trajectories as detached pieces before deposition, and sherd G was burnt and exposed on the surface for some time before entering Pit 17. Likewise sherds M & N were found within Pit 13 and despite exhibiting contrasting features – Sample M is an intensely eroded yellowish rim (Fig. 3, M1) whereas Sample N is a better preserved body sherd featuring sharp breaks, smooth surfaces and an external dark color (Fig. 3, N1) – they belonged to the same incised vessel.

In short, this evidence sheds new light on the terminal stages of these ceramics. Thus, there is room to posit a wide range of mobility – up to 45 m apart (Fig. 1B) – for already broken potsherds on the surface of the temporary camp prior to their final incorporation into the pits. Moreover, the petrographic cross-checking confirms that parts of the same vessels had genuinely different pre-depositional histories (Garrow, 2006; Edwards, 2012; Orton and Hughes, 2013: 265–266). Thus, it has been possible to track differential post-breakage trajectories of sherds from both fine decorated and coarse vessels. This suggests that some time elapsed between the breakage of vessels and their discard. Thus, such fragments might have been piled, recycled or reused for diverse purposes (cf. Chapman and Gaydarska, 2007: 75–77) prior to their definitive abandonment.

4. Concluding remarks

This paper has presented a multi-phase procedure to test sherd-to-vessel associations using the more abundant but often disregarded ceramic items: the non-adjointing potsherds. Beyond the mainstream analyses of provenance and production, technology or post-depositional alterations, the focus has been on the widely ignored pre-depositional circumstances affecting these archaeological ceramics after their fracture. The use of ceramic thin section analysis to collate paired sherds has relied upon technological criteria such as the type, amount, size, roundness and sorting and homogeneity of inclusions, their distribution in

the fabrics, core color, color of the fabric and the presence of voids and cracks. Ceramic petrography has independently tested a series of preliminary macroscopic associations based upon a systematic scoring template (Blanco-González and Chapman, 2014). The results show the reliability of the initial observations, but that only further archaeometric methods can confirm or reject them. Out of the 16 paired sherds, we can confidently state that eight belonged to four vessels (A & B; G & H; I & J; M & N) and four more probably belonged to two vessels (C & D; K & L) but their evidence is weaker, whereas four derived from four different vessels (E, F, O, P). The archaeometric testing of sherd-links has shed light on the last steps in the life-histories of ceramics. In particular, the proposed procedure has opened up new interpretive avenues dealing with the formation of pit deposits made by the earliest pottery using communities in Western Europe. These small-scale groups managed their ceramic refuse according to complex ways of doing, sometimes involving certain delay in between the breakage and the final abandonment of these sherds.

From a methodological point of view an important finding has been that the post-breakage alterations – and concretely fire – do not seem to detract from the applicability of the proposed method. Therefore, this enables matching of sherds with contrasting physical appearance, which otherwise would have been ruled out as possible refits. Moreover, in ceramic petrography it is usually assumed that non-refitting sherds originated from diverse parent vessels. This principle orientates the sampling strategies when characterizing the relative proportions of fabrics within an assemblage, for example in research on provenance determination (e.g. Quinn, 2013: 129). The results presented here demonstrate that this assumption is not always true and this has wider implications. In particular, our study warns scholars against any uncritical inferences of sherd-to-vessel associations when coming across petrographic resemblances between sherds wherever they have been found. Thus, the occurrence of non-conjoining sherds featuring petrographically very closely related thin sections could be regarded as samples from the same vessel, whether they come from the same or different depositional contexts. In short, this procedure expands the scope of sherd-to-vessel determination since it provides a more robust and critical method to cope with macroscopically well-defined potsherds irrespective of whether they are body, undecorated or non-adjointing sherds and irrespective of their contextual associations.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at <http://dx.doi.org/10.1016/j.jas.2014.06.024>.

Appendix

Sample	% Aplastics & voids (Dig. Image Analysis)	No. of grains & voids (Dig. Image analysis)	Matrix	Predominant inclusions	Other inclusions	Accessories	Dominant size of inclusion	Sorting	Common grain shape	Angularity	Pores	Matrix color	Homogeneity	Comments	Interpretation
A	49.97%	2122	Clay-rich, sparse amounts of very fine inclusions	Mono- and polycrystalline quartz	Feldspar, plagioclase, muscovite	Zircon, tourmaline	0.2–1 mm	Moderate	Equant, subhedral	Subrounded, subangular	Elongate channels, often oriented parallel to the vessel wall. Some vughs	Brown/reddish (sherd with two layers)	Heterogeneous	Both sherds have similar clay-rich matrix tempered with mostly medium-sized sand. In Sample B streaks of clay, esp. around larger inclusions. Similarities in matrix, shape and amount of inclusions suggest sherds may belong to same vessel. Digital image analysis shows similar percentual values of non-plastics and voids (Sample A = 50%, Sample B = 48%)	Sherds most likely belonged to same bowl. Sample A was oxidized after breakage. They finished in Pits 1 and 3 (25 m apart)
B	48.35%	2776	Clay-rich, sparse amounts of very fine inclusions	Mono- and polycrystalline quartz	Feldspar, plagioclase, muscovite	Zircon, tourmaline, a piece of charred vegetal matter	0.2–1 mm	Moderate	Equant, subhedral	Subrounded, subangular	Elongate channels, often oriented parallel to the vessel wall. Some vughs	Brown (sherd with two layers)	Heterogeneous	Both samples show sparse amounts of ARFs or weathered rock fragments. ARFs have similar color and composition to matrix in both samples. Both sherds have similar clay-rich matrix tempered with mostly medium-sized sand. Color of fabrics is different. Similarities in matrix, ARFs shape and composition, and inclusions suggest they might have originated from same vessel. However, these observations are inconclusive as digital image analysis indicates very different proportions of voids and non-plastics (Sample C = 37%, Sample D = 29%)	Sherds are most sparse amount of ARFs, probably from Sample E also contains different bowls with similar composition to the matrix. Both sherds are tempered with sand and contain ARFs and limestone. Remarkable differences in size and amount of inclusions.
C	37.38%	3419	Clay-rich, sparse amounts of very fine inclusions	Mono- and polycrystalline quartz	Feldspar, plagioclase, muscovite, rounded ARFs or weathered rock fragments	Zircon	0.1–1 mm	Moderate	Equant-elongate, anhedral-subhedral	Subrounded, rounded	Elongate channels and oriented, some vughs	Orange/reddish (sherd with one layer)	Heterogeneous	Both samples show sparse amounts of ARFs or weathered rock fragments. ARFs have similar color and composition to matrix in both samples. Both sherds have similar clay-rich matrix tempered with mostly medium-sized sand. Color of fabrics is different. Similarities in matrix, ARFs shape and composition, and inclusions suggest they might have originated from same vessel. However, these observations are inconclusive as digital image analysis indicates very different proportions of voids and non-plastics (Sample C = 37%, Sample D = 29%)	Sherds might have belonged to same bowl discarded within Pit 9, but results are inconclusive
D	29.07%	3530	Clay-rich, sparse amounts of very fine inclusions	Mono- and polycrystalline quartz	Feldspar, plagioclase, muscovite, rounded ARFs or weathered rock fragments	Zircon, a piece of charred vegetal matter	0.1–1 mm	Moderate	Equant-elongate, anhedral-subhedral	Subrounded, rounded	Elongate channels that show preferred orientation, some vughs	Dark brown/gray (sherd with one layer)	Heterogeneous	Both samples show sparse amounts of ARFs or weathered rock fragments. ARFs have similar color and composition to matrix in both samples. Both sherds have similar clay-rich matrix tempered with mostly medium-sized sand. Color of fabrics is different. Similarities in matrix, ARFs shape and composition, and inclusions suggest they might have originated from same vessel. However, these observations are inconclusive as digital image analysis indicates very different proportions of voids and non-plastics (Sample C = 37%, Sample D = 29%)	Sherds are most sparse amount of ARFs, probably from Sample E also contains different bowls with similar composition to the matrix. Both sherds are tempered with sand and contain ARFs and limestone. Remarkable differences in size and amount of inclusions.
E	15.57%	3786	Clay-rich, rare amounts of very fine inclusions	Mono- and polycrystalline quartz	Feldspar, plagioclase, muscovite, limestone fragments	Zircon	0.1–1.5 mm	Moderate	Equant, subhedral	Subrounded, rounded	Elongate channels, preferred orientation. Some Planar voids	Brown/reddish (sherd with one layer)	Heterogeneous	Both samples contain sparse amount of ARFs, probably from Sample E also contains different bowls with similar composition to the matrix. Both sherds are tempered with sand and contain ARFs and limestone. Remarkable differences in size and amount of inclusions.	Sherds are most sparse amount of ARFs, probably from Sample E also contains different bowls with similar composition to the matrix. Both sherds are tempered with sand and contain ARFs and limestone. Remarkable differences in size and amount of inclusions.
F	19.92%	2537	Clay-rich, sparse amounts of very fine inclusions	Mono- and polycrystalline quartz	Feldspar, plagioclase, muscovite, limestone fragments, chert fragments	Zircon, a piece of charred vegetal matter	0.1–1.5 mm	Moderate	Equant, anhedral-subhedral	Subrounded, rounded, well rounded	Elongate channels, poorly oriented, some preferred orientation.	Reddish (sherd with one layer)	Heterogeneous	Both samples contain sparse amount of ARFs, probably from Sample E also contains different bowls with similar composition to the matrix. Both sherds are tempered with sand and contain ARFs and limestone. Remarkable differences in size and amount of inclusions.	Sherds are most sparse amount of ARFs, probably from Sample E also contains different bowls with similar composition to the matrix. Both sherds are tempered with sand and contain ARFs and limestone. Remarkable differences in size and amount of inclusions.

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Sample	% Aplatsics & voids (Dig. Image Analysis)	No. of grains & voids (Dig. Image analysis)	Matrix	Predominant inclusions	Other inclusions	Accessories	Dominant size of inclusion	Sorting	Common grain shape	Angularity	Pores	Matrix color	Homogeneity	Comments	Interpretation
G	25.47%	2617	Very fine-grained, moderate amounts of very fine inclusions	Mono- and polycrystalline quartz	Feldspar, plagioclase, muscovite, weathered rock fragments, probably of metamorphic origin	Zircon, tourmaline	0.1–1 mm	Moderate	Equant, anhedral-subhedral	Subrounded, subangular	Some planar voids	Brown/reddish (sherd with two layers)	Heterogeneous	Both sherds contain sparse amount of ARFs. Sample G contains rare amounts of grog with a similar composition to the matrix. Both have similar, very fine-grained matrix. Before that, Sample G tempered with mostly medium-sized sand. Similarities in matrix, pores and non-plastic inclusions suggest they may have belonged to same vessel. Values of non-plastics and voids proportions provided by digital image analysis are also coherent (Sample G = 25.5%, Sample H = 28%).	Sherds confidently belonged to the vessel, and both entered Pit 17.
H	27.95%	2923	Very fine-grained, moderate amounts of very fine inclusions	Mono- and polycrystalline quartz	Feldspar, plagioclase, muscovite, weathered rock fragments, probably of metamorphic origin	Zircon, tourmaline	0.1–1 mm	Moderate	Equant, anhedral-subhedral	Subrounded, subangular	Characteristic elongated and oriented channels are visible. Some vughs	Dark brown (sherd with one layer)	Heterogeneous	Characteristic elongated and oriented channels are visible. Some vughs	tempered with mostly experienced abrasion and fire exposition.
I	38.09%	3687	Calcareous	Monocrystaline Calcite Fragments	Monocrystalline quartz	Muscovite, polycrystalline quartz, ARFs	0.2–1.5 mm	Poor	Most grains are Equant, Euhedral. ARFs elongate, anhedral	Most grains are angular, few grains are subangular, well rounded, and subrounded	Elongate and oriented pores. Micro-cracks are common in the calcite inclusions	Brown/reddish	Heterogeneous	Sherds are the most similar out of those examined in this study. Calcite was likely crushed and added as filler. Similar amount, size and distribution of calcareous inclusions suggest that samples belong to the same vessel. Digital image analysis also shows close proportions of non-plastics and voids (Sample I = 38%, Sample J = 40%).	Sherds are confidently from the same vessel. They finished in different features (Pits 2 and 10)
J	39.93%	3330	Calcareous	Monocrystaline Calcite Fragments	Monocrystalline quartz	Muscovite, polycrystalline quartz, ARFs	0.2–1.5 mm	Poor	Most Grains are equant, euhedral, ARFs elongate, anhedral	Most grains are angular, few grains are subangular, well rounded, and subrounded	More elongate and oriented pores. Micro-cracks are common in the calcite inclusions	Brown/reddish (sherd with two layers)	Heterogeneous	calcareous inclusions suggest that samples belong to the same vessel. Digital image analysis also shows close proportions of non-plastics and voids (Sample I = 38%, Sample J = 40%).	

K	Image analysis Inconclusive	Clay-rich, sparse amounts of very fine inclusions	Mono- and polycrystalline quartz	Feldspar, plagioclase, muscovite, pieces of charred vegetal remains, weathered rock fragments/ARFs	Tourmaline	0.1–1 mm	Moderate	Most grains are equant, subhedral, elongate, subhedral	Subrounded, subangular	Mainly irregular channels and vughs	Brown/reddish (sherd with two layers)	Heterogeneous	Both sherds have similar clay-rich matrix with sand inclusions, however they were tempered with different amounts and sizes of sand. In Sample L the grains vary from very fine to medium, whereas in Sample K the fine grains are almost missing. Sample K contains more charcoal pieces. They are likely parts of different vessels, but this could not be corroborated by digital image analysis	Sherds are probably from different bowls
L	27.90%	Clay-rich, sparse amounts of very fine inclusions	Mono- and polycrystalline quartz	Feldspar, plagioclase, muscovite, pieces of charred vegetal remains, weathered rock fragments/ARF	Tourmaline, chert fragments	0.1–1 mm	Moderate	Most grains are equant, subhedral, elongate, subhedral	Subrounded, subangular	Mainly irregular channels and vughs, some elongated and oriented ones	Brown/reddish (sherd with one layer)	Heterogeneous		
M	50.41%	Clay-rich, sparse amounts of very fine inclusions	Mono- and polycrystalline quartz	Feldspar, muscovite, ARF, weathered feldspar and quartz	Zircon, tourmaline	0.1–0.8 mm	Moderate	Equant-elongate, subhedral	Subrounded, subangular	Elongated channels, showing preferred orientation with vessel wall	Light brown/ yellowish (sherd with two layers)	Heterogeneous	Both sherds have similar matrix tempered with sand, although Sample N has slightly more medium sized grains. This may be the result of incomplete clay preparation. The similarities in matrix, type and amount of inclusions suggest these samples may have belonged to the same vessel. In both sherds the yellowish parts seem to have less aplastic inclusions (probable mixing of clays). Digital image analysis also shows very close proportions of voids and non- plastics (Sample M = 50%, Sample N = 48%)	Sherds confidently derive from same bowl, despite exhibiting strikingly diverse post-breakage alterations: Sample M was intensely eroded (and eventually lost its external surface) and was subject to oxidation by fire (pale orange external color), whereas Sample N is 'freshly broken' and features dark external color. After such alterations they entered Pit 13
N	48.27%	Clay-rich, sparse amounts of very fine inclusions	Mono- and polycrystalline quartz	Feldspar, muscovite, ARF, weathered feldspar and quartz	Zircon, tourmaline	0.1–0.8 mm	Moderate	Equant-elongate, subhedral	Subrounded, subangular	Elongated channels, showing preferred orientation with vessel wall	Dark brown (sherd with two layers)	Heterogeneous		
O	14.93%	Clay-rich, sparse amounts of very fine inclusions	Mono- and polycrystalline quartz	Feldspar, muscovite, plagioclase, grog/ ARFs, limestone fragments	Zircon, tourmaline	0.1–0.8 mm	Moderate	Equant, anhedral- subhedral	Subrounded, subangular	Vughs. Small elongated channels randomly distributed. Stress cracks rather than voids	Light brown/ reddish (sherd with two layers)	Heterogeneous	Both sherds are tempered with sand, but their basic inclusions and clay matrix are different. These samples probably belong to different vessels.	Sherds are confidently from two different large decorated vessels, included into Pit 13
P	22.54%	Very fine- grained fabric with moderate amounts of very fine-grained inclusions.	Mono- and polycrystalline quartz	Feldspar, muscovite, plagioclase, grog/ ARFs, coarse limestone fragments	Zircon, tourmaline	0.1–0.8 mm	Moderate	Equant, anhedral- subhedral. Few elongate	Subrounded, subangular	Elongated channels weakly to moderately oriented, vughs	Dark brown (sherd with two layers)	Heterogeneous	Digital image analysis indicates very large differences in the proportion of voids and non-plastics (Sample O = 15%, Sample P = 22.5%)	

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